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PRELIMINARY COST AND MISSION VALUE COMPARISONS FOR PLANETARY PROBES DELIVERED BY ADVANCED PROPULSION SYSTEMS

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SUMMARY

Preliminary cost and mission value comparisons are made for three advanced propulsion systems: an advanced chemical system, an improved solid-core nuclear rocket engine with a 25-kilowatt auxiliary powerplant, and a nuclear-electric system, all three of which are candidate systems for delivering advanced probe spacecraft. The comparison of these systems is made on the basis of transportation cost divided by the expected value of the data returned to Earth. The analysis shows that for the Mercury Orbiter mission and for missions to the outer planets with a high data requirement, the nuclear-electric system emerges as the best system based on this criterion. For the Venus Orbiter mission, the advanced chemical propulsion system is best.

INTRODUCTION

Recent comparisons of alternative future space propulsion systems have quite properly included considerable effort to estimate the "transportation" costs (i.e., dollar cost for given payload mass) associated with each candidate system. Such estimates are a necessary step in developing a balanced comparative analysis of future propulsion systems. They are not meaningful when considered alone, however, because they do not account for the effects that different propulsion systems may have upon the payload and the benefits received from the mission. Consider, for example, a nuclear-electric spacecraft and a chemical-propulsion spacecraft that carry equal payload masses to a given destination. The nuclear-electric spacecraft has ample electric power (after the primary propulsion phase is over) to accommodate a large amount of experiment and communication gear. For chemical-propulsion spacecraft, the experiment and communication gear must be decreased in size (and hence, in data-gathering capacity) in order to include an auxiliary payload powerplant. The difference can be very significant for missions involving high-powered experiments and/or high rate data transmission.

It must be clearly understood that the entire value of and justification for any space probe mission resides in the data transmitted back to Earth. Data, not mass, is what we are paying for. Hence, to obtain a balanced viewpoint, the criterion employed in any comparison must reflect the mission's worth as well as its cost. In this report we propose an initial approach by assuming that the mission value V is equal to the expected value of a weighted summation of the data generated by the sensor-communication-powerplant complex. An appropriate criterion of merit is then $\$/V$ (i.e., dollar cost per unit data return).

In the following analysis and discussion, this proposed criterion is developed and applied to representative missions using chemical, solid-core nuclear, and nuclear-electric propulsion systems. The object of this exercise is merely to demonstrate that using this criterion in place of dollar cost per unit payload mass can result in a complete reversal of what would appear to be the most and least desirable propulsion systems. The actual numerical results should be understood as preliminary since (1) the transportation-cost data used herein is itself preliminary and requires verification and (2) the real mission value may depend upon other attributes of the data, such as relevance, novelty, timeliness, and technical quality, in addition to total quantity.

ANALYSIS

The final product of any interplanetary probe mission being the data transmitted back to Earth, an appropriate basis of comparison between propulsion systems for this type of mission would be the total cost per unit of data returned. In order to make such a comparison, it is necessary to obtain expressions for the data rate associated with each type of propulsion system. These expressions, developed below for chemical, solid-core nuclear, and nuclear-electric propulsion systems, are then combined with vehicle cost estimates to compare propulsion systems on the basis of this criterion.

Costs

A NASA HQ-OART/Inter-Center Advanced Propulsion Study (results unpublished) conducted in 1971 has produced a set of comparative cost estimates for a representative group of mission destinations, payload masses, and propulsion systems. Basically, the study compares direct operational transportation costs (not including development costs) assuming launch via fully reusable space shuttle ($\$5\times10^{6}$/launch) in the 1980's. Total mission costs, which would also include prorated development cost and the cost of the payload, were not estimated. Some selected results from that study are presented in table I and are used herein for illustrative purposes.

Some explanation of the nuclear propulsion system costs is necessary. The numbers presented are based on a mission profile in which the nuclear stage imparts sufficient velocity to place the spacecraft on its transfer orbit and is then discarded. If additional velocity changes are required, they would be obtained from a chemical propulsion system. A proposal has been made to use a NERVA type rocket engine as a heat source to generate electric power when the engine is not operating (ref. 1). With such a system, the propulsion stage would, of course, have to be retained in order to use the electric power. The costs for this case, which would have to account for the different mission profile and also for the added cost of the auxiliary powerplant, are not available. The costs that are assumed herein for this case are equal to those for the case in which the nuclear stage is discarded; so, they must be considered as a lower bound to the actual values.

A perusal of table I would indicate that the advanced chemical propulsion system is preferable by a factor of about 2 for most of the missions shown; that is, it is only half as costly as the others for the assigned task of delivering 2000 kilograms to the indicated destination. Since the missions shown are quite representative of future planning, it would be difficult, on the basis of the data shown, to avoid the conclusion that neither NERVA nor the nuclear-electric system is worth developing. On the other hand, the three systems, although delivering equal payload, yield markedly different data return as will now be shown.

Payload Mass Allocation

The following mathematical model of the gross payload mass was constructed in order to obtain expressions for data rate as a function of gross payload mass for the three propulsion system types. The general relation for gross payload is

$$M_g = M_{st} + M_f + M_c + M_s + M_p$$

where M_g is the gross payload mass, M_{st} is the structure mass, M_f is the mass of systems not greatly affected by spacecraft mass and power (includes systems such as guidance, attitude control, etc.), M_c is the mass of the communication system, M_s is the mass of the sensors, and M_p is the mass of the payload powerplant. (Symbols are also defined in appendix A.) Some of these subsystem masses can be modeled as follows:

$$M_{st} = K_{st}M_g$$

where K_{st} is the structure fraction

$$M_c = M_{ca} + \alpha_c P_c$$

where M_{ca} is the mass of the communication system antenna, α_c is the specific mass of the communication system excluding the antenna, the P_c is the power required by the communication system

$$M_s = M_{sp} + M_{sa}$$

where M_{sp} is the mass of the passive sensors, which require very little power (such as TV and particle and fields detectors), and M_{sa} is the mass of the active sensors, which require high power (such as radar and lidar),

$$M_{sa} = M_{saa} + \alpha_{sa} P_{sa}$$

where M_{saa} is the mass of the active sensor antenna, α_{sa} is the specific mass of the active sensor system excluding the antenna, and P_{sa} is the power required by the active sensors

$$M_p = \alpha_p P_p$$

where α_p is the specific mass of the payload powerplant and P_p is the power produced by the payload powerplant.

Combining these equations results in the following general expression:

$$M_g(1 - K_{st}) = M_f + M_{sp} + M_{saa} + \alpha_{sa} P_{sa} + M_{ca} + \alpha_c P_c + \alpha_p P_p$$

It can be rearranged as:

$$\alpha_{sa} P_{sa} + \alpha_c P_c + \alpha_p P_p = M_g(1 - K_{st}) - M_f - M_{sp} - M_{saa} - M_{ca} \equiv M'$$

Let the ratio of the power required by the active sensors to that required by the communication system be designated by the symbol K_p, that is,

$$K_p = \frac{P_{sa}}{P_c}$$

This ratio, which will be treated as a parameter in the analysis, is discussed in the section Power Ratio.

Power Requirements

An additional assumption made at this point is that the active sensors and the communication gear are operating at the same time. With the assumption that the data rate for each of these systems is proportional to the input power, as the mass was assumed to be, it can be shown that simultaneous operation results in the highest data rate. Cyclic operation of first the active sensor system and then the communication system results in a lower data rate, even if a data storage system required no mass. (This is demonstrated in appendix B.)

Chemical propulsion. - For a spacecraft delivered by a chemical propulsion system, the payload powerplant must provide the power for the sensors and the communication system; that is,

$$P_p = P_{sa} + P_c$$

Applying this constraint and using the parameter K_p results in the following expression for the communication power:

$$P_c = \frac{M'}{(K_p + 1)\alpha_p + K_p \alpha_{sa} + \alpha_c}$$

Nuclear propulsion. - A study of the feasibility of using the NERVA rocket engine as a heat source for generating 25 kilowatts of electric power has recently been completed (ref. 1). A significant conclusion of the study is: If the electric power is used to reliquify boiloff hydrogen on an interplanetary mission, the propellant recovery is expected to be an order of magnitude greater than the hardware weight of the NERVA electrical system, resulting in improved performance for the NERVA rocket. Furthermore, at the mission destination, the NERVA electric powerplant can be used to supply all or part of the required power to the sensors and communication system. For the case in which the 25 kilowatts are sufficient, the communication power is

$$P_c = \frac{M'}{K_p \alpha_{sa} + \alpha_c}$$

For the case in which more than 25 kilowatts are needed, the payload powerplant would have to supply the additional power, that is,

$$P_p = P_{sa} + P_c - 25$$

Applying this constraint results in the following expression for communication power:

$$P_c = \frac{M' + 25\alpha_p}{(K_p + 1)\alpha_p + K_p\alpha_{sa} + \alpha_c}$$

In this analysis, the term nuclear propulsion system will be used to designate an improved NERVA system with the capacity to produce 25 kilowatts of electric power.

Nuclear-electric propulsion. - No powerplant need be included in the gross payload mass delivered by a nuclear-electric propulsion system provided the propulsion powerplant can supply all the required power. Let us assume this to be the case. The communication power for a spacecraft delivered by a nuclear-electric propulsion system is

$$P_c = \frac{M'}{K_p\alpha_{sa} + \alpha_c}$$

For all three propulsion systems considered, the power used by the sensors and the communication system P_u is given by the following expression:

$$P_u = (K_p + 1)P_c$$

Data Rate

For a given set of communication system parameters, the data rate is directly proportional to the power supplied to the communication system, and inversely proportional to the square of the communication distance, that is

$$\dot{u} = K_c \frac{P_c}{R^2}$$

Communication system parameters such as transmitter efficiency, transmitting and receiving antenna gains, system noise temperature, signal to noise ratio, link frequency, bandwidth, and choice of modulation system determine the value of the proportionality constant. The data rate is expressed in units of 10^6 bits per second, megabits per second. (A typical television picture with compression might require 1 Mbit. To duplicate the commercial rate of 30 pictures per second, 30 Mbit/sec would be needed.)

The communication distance is expressed in units of astronomical units (AU). The product of the data rate and the square of the communication distance is independent of the mission destination. This quantity, referred to herein as the communication param-

eter, has the dimensions of megabits per second times the square of the communication distance in AU's.

The communication parameter can be related to the gross payload by substituting the expressions for the communication power, developed in the previous section, into the following equation:

$$\text{Communication parameter} \equiv \dot{u}R^2 = K_c P_c$$

To obtain values for the communication parameter, numerical values for the quantities in the expression must be assumed.

Communication system constant, K_c. - The assumed value of K_c is 6.7 megabits per second times R_{AU}^2 per kilowatt, or (6.7 Mbit/sec × R_{AU}^2/kW). This value is twice that of the design value for the proposed Thermoelectric Outer Planet Spacecraft (TOPS) communication system transmitting at an S-band frequency to the 64-meter (210-ft) DSS antenna. This increase of a factor of two could be obtained by doubling the gain of the TOPS antenna (increasing the diameter from the present 4.3 m (14 ft) to 6.1 m (20 ft)). It should be noted that the value of K_c can be increased by a factor of 10 if an X-band frequency is used; however, weather conditions restrict the use of these higher frequencies.

Gross payload mass, M_g. - A value of 2000 kilograms (4410 lbm) is assumed for the gross payload mass for all cases. This value was used in the cost study which yielded the data of table I.

Structure mass, M_{st}. - The structure fraction is assumed to be 10 percent of the gross payload mass. The TOPS design has a structure fraction of 12.6 percent for a gross payload of 660 kilograms (1450 lbm). The Navigator study (ref. 2) estimates a 10-percent structure fraction for larger gross payloads, so this value is used.

Fixed mass, M_f. - A value of 227 kilograms (500 lbm) is assumed for the fixed housekeeping mass as being typical for a large spacecraft. Both the TOPS and the Navigator spacecraft designs allocate approximately this amount of mass for housekeeping functions.

Communication system mass, M_c. - In the minimization of communication system mass, it generally turns out that the communication antenna should be quite large, especially if lightweight antenna material is assumed to be used. However, the maximum size is restricted by packaging constraints and by the more demanding attitude control requirements for larger antennas. A diameter of 6.1 meters (20 ft) was selected as a reasonable size for the Navigator spacecraft, and this value is used in this analysis. The estimated mass of 159 kilograms (350 lbm) (5.4 kg/m^2 (1.1 lbm/ft^2)) from the Navigator study is also used. The specific mass of the communication system excluding the

antenna is taken to be 11.3 kilograms per kilowatt (25 lbm/kW). This value is also based on the Navigator study, for which the input power to the communication system is on the order of tens of kilowatts. For comparison, the value for TOPS is over 408 kilograms per kilowatt (900 lbm/kW), but the input power is only 100 watts.

Sensor mass, M_s. - The science payload of TOPS, which includes only passive sensors is 100 kilograms (220 lbm). The mass of the low-power sensors for the Navigator spacecraft on a planetary mission is estimated to be 195 kilograms (430 lbm). In this analysis a value of 181 kilograms (400 lbm) is assumed for the mass of the passive sensors. The mass of the active sensor systems and the required operating power are difficult to estimate because no hardware has yet been developed. Two recent studies (refs. 3 and 4) of the general subject of remote sensors, both active and passive, and the support requirements for these sensors are available, so that some predictions can be made. These studies include scaling laws relating performance requirements of candidate remote sensor systems. One type of sensor system of considerable interest and for which a large amount of power is required is synthetic aperture radar. A typical estimated value of specific mass for this type of sensor system, excluding the antenna, is 22.7 kilograms per kilowatt (50 lbm/kW). This value is assumed to apply to all active sensor systems. The radar antenna for most missions will probably be limited in size by packaging constraints and attitude control requirements as in the case of the communication antenna. Because of the rectangular shape of the radar antenna, the packaging constraint will probably not be as severe as for the communication antenna, and a greater area can probably be used. An area of 46.2 square meters (500 ft^2) and a mass of 227 kilograms (500 lbm) (4.88 kg/m^2; 1 lbm/ft^2) are assumed for this item.

Payload powerplant mass, M_p. - In the low power range (<10 kW), solar cell power systems have the lowest value of specific mass, followed by systems that utilize a radioisotope heat source. For missions to the outer planets, solar cell power is reduced so drastically that only systems with a radioisotope heat source are practical; so, a specific mass for this type of system is used for missions to the outer planets. Solar cell power is assumed to be used for the inner planet missions. According to recent projections (ref. 5), development efforts to increase surface temperatures of encapsulated-fuel of radioisotope thermoelectric generators (RTG) should lead to power levels up to 1 kilowatt, with a specific powerplant mass from 227 to 302 kilograms per kilowatt (500 to 667 lbm/kW) and a useful life of over 10 years. Reference 5 also indicates that achievement of high surface temperatures would permit coupling a radioisotope heat source with a high efficiency Brayton-cycle conversion system. The projected value of specific powerplant mass for unmanned missions is 302 kilograms per kilowatt (667 lbm/kW) in the 6- to 10-kilowatt power range. Based on these projections, an optimistic value of 227 kilograms per kilowatt (500 lbm/kW) was chosen as the specific mass of the payload powerplant for outer planet missions. For comparison, the value for TOPS

is about 308 kilograms per kilowatt (680 lbm/kW). A value of 22.7 kilograms per kilowatt (50 lbm/kW) at 1 AU is assumed for the solar cell powerplant. The output power increases by as much as 30 percent as the distance to the sun is reduced and decreases to about 50 percent of its 1 AU value at Mars. A range of solar cell specific mass, 17.0 to 45.4 kilograms per kilowatt (37.5 to 100 lbm/kW), is considered to account for this variation.

Power ratio, K_p. - To maximize the data rate, the sensors and communication system should be sized so that the data are transmitted at the same rate that processed data are being generated. (Raw data from the sensors can be processed on board the spacecraft so as to reduce the communication requirement.) This is shown in appendix B to be better than operating the sensors for a while, processing and storing the data, and then transmitting the processed data. Sizing the systems to maximize the data rate amounts to determining a value of the ratio K_p for the particular mission. For a spacecraft that carries only passive sensors, very little power is required for their operation, and the value of the ratio is small, especially for the distant planets. For spacecraft that carry active sensors requiring a large amount of power, the ratio would be large. Not much more can be said about this ratio unless a particular planetary target is selected and a more detailed analysis of the sensors and communication system is made. Let us proceed to determine whether some general results can be obtained without going into considerable design detail. The ratio will be assigned values of 0, 1, and 10.

Comparison of Data Rates

Comparison of the data rates for spacecraft delivered by each of the three propulsion systems is made in figure 1, in which the communication parameter is presented for the three values of the power ratio, 0, 1, and 10, for both the inner and outer planet missions. The communication parameter, as defined earlier, is the product of the data rate in megabits per second and the square of the communication distance in astronomical units. For any particular mission, the equivalent number of TV pictures per second can easily be obtained by dividing the communication parameter by the square of communication distance in units of AU's and the number of megabits per TV picture. For example, suppose that a nuclear-electric propulsion system is used for a mission to Jupiter (fig. 1(a)) and the active sensor power requirement is small ($K_p \approx 0$). The communication parameter would have a value of 600 Mbit/sec $\times$ R^2_{AU}. Suppose also that 1 megabit of data was needed for one TV picture. At opposition when the distance from Jupiter to Earth was approximately 4.2 AU, the picture rate would be 34 pictures per second, or about the commercial rate. At conjunction the distance would be 2 AU's greater or 6.2 AU, and the picture rate would drop to 15.6 pictures per second.

For the outer-planet missions, the data rates for spacecraft delivered by the chemical, nuclear, and nuclear-electric propulsion systems, respectively, are in the ratio of 1 to 6.6 to 21 for K_p equal to zero, 1 to 6.6 to 14 for K_p equal to unity, and 1 to 6.6 to 11 for K_p equal to 10. For larger values of K_p the ratio of data rates remains at 1 to 6.6 to 11. For the inner-planet missions, the corresponding ratios of data rates (for a specific powerplant mass of 22.7 kg/kW (22.7 lbm/kW)) are 1 to 1.6 to 3 for a value of K_p equal to zero, 1 to 1.6 to 2.3 for K_p equal to unity, and 1 to 1.6 to 2 for K_p equal to 10. The ratio remains at 1 to 1.6 to 2 for larger values of K_p. Comparing the data rates for the inner- and outer-planet missions, it can be seen that the data rate advantage of the nuclear and nuclear-electric systems over the chemical system is much lower for the inner-planet missions. This is due to the lower specific mass of the payload powerplant used for the inner-planet missions.

Comparison of Electric Power Requirements

The electric power used by the sensors and communication system is presented in figure 2. For any particular value of K_p, more power is used, of course, by a spacecraft delivered by a nuclear-electric propulsion system than by one delivered by the other systems. For a value of K_p equal to zero, the nuclear-electric spacecraft requires 89 kilowatts of electric power. This rather high value is still below the typical value of 120 kilowatts for a system of this type; so, it can supply the required power. In the case of nuclear propulsion, more than 25 kilowatts of power is required by a spacecraft of this size; so, a small payload powerplant is needed to provide the extra power. The payload mass of the chemical system must, of course, contain a powerplant to supply all of its power requirements. For the outer-planet missions the chemically delivered spacecraft of this size requires about 4 kilowatts of electric power; for the inner-planet missions, from 15 to 36 kilowatts of electric power is needed. The ratios of power used by spacecraft delivered by chemical, nuclear, and nuclear-electric propulsion systems for any particular value of K_p are the same as the corresponding ratios of data rates.

Mission Values

Comparing propulsion systems solely on the basis of cost to deliver a specified payload mass implicitly assumes that the value of the mission as measured by the returned data is the same in all cases. This is one extreme. On the other hand, assuming that the mission value is directly proportional to the data rate capability and comparing systems on the basis of cost per unit data rate can be considered to be another extreme.

Probably neither is a good description of mission value, but they do represent the limits of a range in which the "correct" description may lie. An examination of mission values and the development of a spectrum of mission values which extends between these extremes is presented in the following sections.

Classification of probe missions. - Probe missions can be roughly divided into three classes: (1) those in which only a specified amount of data is required, (2) those in which, after a specified initial quantity of data is received, additional data have some progressively lower value or importance, and (3) those in which all data are considered to have more or less equal value. An example of the first class is a mission in which a static body such as an asteroid is to be mapped. At the other extreme, the third class would include a probe mission to observe some dynamic process on a body over a long period of time (e.g., to observe the Martian weather). The second class is the most general, including missions which would both survey a body and continue to monitor its processes. It can be considered to be a combination of the first and third classes of missions.

Since only a specified amount of data is required for the first class of missions, a high data rate has the effect of reducing the time required to obtain this data. If reduced time were not important, the mission value would be the same in all cases; however, there would be an advantage in a high data rate if system reliability were a significant question, the lower operating time implying a higher probability of success.

For the third class of missions, the same value is placed upon the data obtained early in the mission as upon that obtained later on. For this case, a high data rate would permit the phenomena to be observed in more detail within a given period of time. The value of the information would probably rise with this capability. In the absence of any other information, it seems reasonable to assume that the mission value is equal to the product of the data rate and the expected life of the system (or the expected value of the data). Reliability would be an important consideration in determining expected life.

The second class of missions represents intermediate cases. It is assumed, quite arbitrarily, that the value of each bit of data is the same until a specified amount is obtained and, thereafter, it decreases exponentially. A rapidly decaying exponential curve approaches the data value assignment of the class one missions; whereas, a slowly decreasing exponential curve approaches that of the class three missions. Reliability is an important consideration for this class of missions as it was for the two extreme classes. The mission value criterion considered appropriate for this case is the expected value of the "valued" or weighted data, based on particular reliability assumptions. A derivation of this criterion is presented in what follows. It should be noted that the expression is quite general and can be used to determine mission values for the class one and class three missions at its limits.

Derivation of mission value criterion. - The following rather arbitrary assumptions are made. The first is that the total amount of data u obtained over the long term

(short term variations being averaged out) is directly proportional to the time of operation t. The proportionality constant is the data rate for that particular system $\dot{u}$:

$$u(t) = \dot{u}t \qquad t \geq 0$$

Furthermore, at time t_1, the base data quantity u_1 will have been obtained.

$$u(t_1) = \dot{u}t_1 = u_1$$

The second assumption involves the data value system. The value of each bit of data v is assumed to be the same until the base data quantity is obtained; thereafter, the value is reduced according to a negative exponential curve with a decay constant of nu_1.

$$\begin{aligned} v &= 1 \qquad 0 \leq u < u_1 \\ &= e^{-(u-u_1)/nu_1} \qquad u \geq u_1, \qquad n \geq 0 \\ &= e^{(1-t/t_1)/n} \qquad t \geq t_1 \end{aligned}$$

The number n will be referred to as the learning constant. A zero value of learning constant is appropriate for a class one mission; an infinite value for a class three mission.

The third assumption is that the failure distribution of the overall system f is a negative exponential curve with a mean time to failure equal to m. (This type of curve has been found to adequately characterize the failure of electronic equipment.)

$$f(t) = \frac{1}{m} e^{-t/m} \qquad t \geq 0, \qquad m > 0$$

If the system had an unlimited life, that is, infinite m, an expression for the maximum weighted data received $uv(\infty)$ can be obtained from the equations associated with the first two assumptions.

$$\begin{aligned} uv(\infty) &= \int_0^\infty \dot{u}v\,dt = \int_0^{t_1} \dot{u}\,dt + \int_{t_1}^\infty \dot{u}e^{(1 - t/t_1)/n}\,dt \\ &= (n + 1)u_1 \end{aligned}$$

For a finite value of system life, the weighted data received up to time t is given by

$$uv(t) = \int_0^t \dot{u}\,dt = \dot{u}t \qquad t < t_1$$

$$\left.\begin{aligned} &= u_1 + \int_{t_1}^{t} \dot{u}e^{(1-s/t_1)/n}\,ds \\ &= u_1\left\{1 + n\left[1 - e^{(1-t/t_1)/n}\right]\right\} \end{aligned}\right\} \quad t \geq t_1$$

With the expression for the failure distribution from assumption three, the expected value of the weighted data called the mission value is obtained as follows:

$$V \equiv E[uv] = \int_0^\infty uv(t)f(t)dt$$

$$= \int_0^{t_1} \dot{u}t\left(\frac{1}{m}\right)e^{-t/m}\,dt + \int_{t_1}^{\infty} u_1\left\{1 + n\left[1 - e^{\left(1 - t/t_1\right)/n}\right]\right\}\frac{1}{m}\,e^{-t/m}\,dt$$

$$= \dot{u}m\left[1 - \left(\frac{\dot{u}m}{\dot{u}m + nu_1}\right)e^{-u_1/\dot{u}m}\right]$$

$$= u_1Q\left[1 - \left(\frac{Q}{Q + n}\right)e^{-1/Q}\right]$$

where

$$Q = \frac{\dot{u}m}{u_1} = \frac{m}{t_1}$$

The ratio of the expected value of the weighted data to the total weighted data received if the system had unlimited life will be called the relative mission value and is given by

$$\text{Relative mission value} \equiv \frac{E(uv)}{uv(\infty)} = \frac{Q}{n+1}\left(1 - \frac{Q}{Q+n} e^{-1/Q}\right)$$

Figure 3 shows relative mission value as a function of the parameter Q for various values of the learning constant n. The figure permits the evaluation of the effect of mission parameters upon mission value.

RESULTS AND DISCUSSION

Effect of Data Rate on Mission Value

Suppose that the value of the learning constant n is zero (class one mission) and, furthermore, that the data rate is so high that the time to obtain the base data quantity is small compared with the mean time to failure. It can be seen from figure 3 that this case, corresponding to a large value of Q, yields a relative mission value of nearly unity, and the increase in mission value obtained by increasing the data rate is small. (The actual mission value for this case is nearly equal to the base data quantity.) On the other hand, if the time required to obtain the base data quantity is comparable to, or larger than the mean time to failure (a value of Q less than or equal to unity) the figure indicates that a substantial increase in mission value can be obtained by raising the data rate.

Suppose now that a high value for the learning constant, for example 100 to 1000, best describes the weighting of the data. (This case approaches the class three mission.) The figure shows that the relative mission value for this case increases almost linearly with the parameter Q. For a particular mean time to failure and base data quantity, this is equivalent to an almost linear increase with the data rate. (The actual mission value for this case approaches the product of the data rate and the mean time to failure.) With a lower value of learning constant (a more typical class two mission), a given percent increase in data rate produces a smaller percent increase in relative mission value.

Effects of Base Data Quantity and Learning Constant on Mission Value

These effects can best be seen by referring to the expression for mission value derived in the preceding section.

If the base data quantity is so large that the time required to transmit it is much longer than the mean time to failure (small Q), the expression for mission value approaches that of the class three missions; that is, the data rate times the expected life

of the system. (The mission value in this case would be less than the base data quantity.) This is true for all values of the learning constant. For this situation, the mission value obtained with different systems is approximately proportional to the data rates associated with these systems.

On the other hand, if the base data quantity is sufficiently small that the time required to transmit it is short compared with the mean time to failure (large Q) and if, in addition, the learning constant is small, the expression for the mission value approaches that of the class one missions; that is, the base data quantity. (The mission value in this case is smaller than the product of the data rate and the mean time to failure.) With a large value of learning constant, even for a small value of base data, the expression for mission value again approaches that for the class three missions.

The significant points to be observed are these: For any particular values of data rate and mean time to failure, an increase in the base data quantity and/or in the learning constant has the effect of tending to change the mission into a class three mission, for which mission value is proportional to data rate; a decrease in base data requirement and/or in the value of learning constant has the effect of tending to change the mission into a class one mission, for which the mission value is constant.

Effect of System Lifetime on Mission Value

Notice that the abscissa of figure 3 is proportional to the product of the data rate and the mean time to failure. In a previous section, the effect of data rate on relative mission value was examined for various fixed values of mean time to failure. If the data rate is now held fixed, a change in mean time to failure would have the same effect on relative mission value as would a change in data rate. For a given data requirement (a base data quantity and a learning constant), a given increase in mission value can be obtained by either increasing the data rate by a certain percent or, instead, by increasing the mean time to failure by that same percent. Certainly every reasonable effort will be made to design a long lifetime data gathering and communication system; however, there are practical limits. At some point, in order to increase the value of the mission, it would be more practical to increase the data rate.

Propulsion System Comparison Based on Cost Per Data Rate

The value of the mission (as defined in this analysis) lies in the data received, not in the data rate. However, it is convenient to first compare the propulsion systems on the basis of cost per unit data rate to identify those missions for which a particular pro-

pulsion system would always have a lower cost per unit data return regardless of the data requirement and the system lifetime.

Let us first compare the propulsion systems having their own powerplants to determine which of the two have a lower cost per unit data rate. It can be seen from table I that the cost of the nuclear-propulsion system is greater than that of the nuclear-electric system for all the missions listed. Figure 1 indicates that the data rate of the nuclear-propulsion system is always less than that of the nuclear-electric system - half as much in most cases. Consequently, of the two systems having their own powerplants, the nuclear-electric system provides the lower cost per unit data rate.

Now let us compare the data rates from a chemical system and a nuclear-electric system. Referring to table I, it can be seen that the cost of a nuclear-electric system is approximately twice that of the chemical system for the outer-planet orbiter missions listed (Jupiter, Saturn, and Uranus). Figure 1 indicates that for these missions the data rate for a spacecraft delivered by a nuclear-electric system is from 11 to 21 times that of a chemically delivered spacecraft. By doubling the mass of the spacecraft delivered chemically (by two launches, for example), the cost would be equal to that of the nuclear-electric system, and the data rate would be doubled. For the same cost, the data rate of the nuclear-electric system would be from 11 to 21 times that of the original chemical system data rate, or from 5 to 10 times the data rate of the scaled-up chemical system. For the outer-planet missions, the lower cost per unit data rate is obtained from a nuclear-electric propulsion system.

For the inner-planet missions, no such generalization can be made. For the Venus Orbiter mission, the cost of the chemical system is about one third that of the nuclear-electric system, which has a data rate of only from 1.8 to 2.5 times that of the chemical system. So, the scaled-up chemical system has a slightly lower cost per unit data rate. In the case of the Mercury Orbiter mission, the cost of the chemical-propulsion system is about the same as that of the nuclear-electric system and the nuclear-electric data rate is again 1.8 to 2.5 times that of the chemical system. In this case a nuclear-electric propulsion system would offer a lower cost per unit data rate by this 1.8 to 2.5 factor.

Propulsion System Comparison Based on Cost Per Data Return

As was pointed out in the section Mission Values, a comparison of propulsion systems on the basis of cost alone represents one extreme, and a comparison on the basis of cost per unit data rate represents the other extreme of a spectrum of real missions. If a particular propulsion system offers the best performance at both extremes when compared with other systems, it is best for all missions on the basis of cost per unit data return, regardless of the data requirement and the system lifetime. As a conse-

quence of this fact, for the Venus Orbiter mission, the chemical system always offers the lowest cost per unit data return because it has the lowest cost and it also has the lowest cost per unit data rate. Also, for the Mercury Orbiter mission, the nuclear-electric system offers the lowest cost per unit data return because it has a cost about equal to the chemical system (the small difference is not significant in the preliminary cost study) and the lowest cost per unit data rate.

For each of the outer-planet missions considered, the chemical-propulsion system cost is lowest but the nuclear-electric system has the lowest cost per unit data rate. So, the system which offers the lowest cost per unit data return for these missions depends on other mission factors; that is, the data requirement and the system lifetime.

The effects of these factors are illustrated for several outer-planet missions in figures 4 to 6. In each example, the cost per unit data return for both chemical and nuclear-electric propulsion systems is presented over a range of values of mean time to failure. This cost criterion for the nuclear-propulsion system would always be higher than that for the nuclear-electric system for the reasons presented in the preceding section and is presented only in the first example.

Jupiter orbiter mission. - The following rather arbitrary assumptions were made for this mission:

Ratio of active sensor power to communication power, K_p 1
Learning constant, n . . . . 0 (class one mission)
Base data quantity, u_1, Mbit . . . . 2×10^7

This particular value of base data quantity will be discussed in the next mission example.

The propulsion system costs and data rates are -

	Chemical	Nuclear	Nuclear-electric
Cost, \$	19×10^6	51×10^6	38×10^6 (from table I)
Data rate, Mbit/sec	0.36	2.40	5.16 (from fig. 1)

With these values for data rate and base data quantity, mission values can be obtained from figure 3 for a range of mean time to failure. The cost of each system divided by its mission value is presented in figure 4 as a function of mean time to failure. It can be seen from the figure that the crossover point of the two curves occurs at one year. If a mean time to failure of greater than a year can be achieved, the chemical propulsion system offers the better performance; otherwise, the nuclear-electric propulsion system performance is better. The time required for each system to transmit the base data quantity is indicated by an asterisk on the curves.

The same figure can be used for other values of base data quantity if it is scaled properly. Suppose the required base data quantity is changed by some factor. If the abscissa is multiplied by this factor and ordinate divided by this same factor, the figure will correctly represent the new case. As a result of this scaling property the mean time to failure at which the two curves cross is directly proportional to the base data quantity. For example, if the base data quantity were increased by a factor of two (to 4×10^{7} Mbit), the mean time to failure of the crossover point would be increased from one to two years, and the cost per unit data return at this point would be decreased from two to one dollar per megabit.

Saturn orbiter mission. - The procedure followed for the Jupiter Orbiter mission was repeated for a Saturn orbiter mission using the same assumptions. In this case, the assumed value of the base data quantity might represent the data needed for a radar map of Titan, the largest of Saturn's moons, with a resolution of 5 meters and a grey scale of 6 (64 shades of grey). The data rates for the Saturn mission are approximately one fourth those for the Jupiter mission, Saturn being about twice as far from the Earth. The comparison of the costs per unit data return is presented in figure 5. Notice from the figure that the mean time to failure at which the two curves cross is three years. If a system with an expected life greater than 3 years can be built, the chemical system would be the better propulsion system for this mission; otherwise, the nuclear-electric propulsion system would be better.

Uranus orbiter mission. - The last example is for a Uranus Orbiter mission. Again the assumptions are the same as those for the Jupiter Orbiter mission. The data rates for this case are approximately one sixteenth of those for the Jupiter mission because Uranus is about four times as far from Earth. The propulsion system comparison is presented in figure 6. The crossover value of mean time to failure for this case is about 13 years, a considerable increase over the 3 years for the Saturn mission. This high system lifetime would be difficult to obtain, so the nuclear-electric system would probably be the better system for this mission with the assumed data requirement.

From these three mission examples, it can be seen that, for missions to the outer planets, which have high data requirements, the required lifetime of a spacecraft delivered by a chemical-propulsion system is extremely high. For reasonable values of system lifetime, the nuclear-electric propulsion system offers the lowest cost per unit of data return.

It should be noted that in determining the mean time to failure of a spacecraft delivered by a particular propulsion system, proper account must be taken of the operational history of the powerplant before it is used for data gathering and transmission. In the nuclear-electric case, the powerplant would have been operating at full power for 10 000 to 20 000 hours to provide thrust before it is operated at part power at the planet. For the chemical propulsion case, the RTG payload powerplant would necessarily be

supplying electrical power continuously from the beginning of the mission, even though it was not needed during the outbound flight.

CONCLUDING REMARKS

A preliminary comparison of advanced propulsion systems for future planetary probe missions has been made on the basis of cost per unit data return. The study revealed that the nuclear-electric propulsion system offers the best performance based on this criterion for the Mercury orbiter mission and the outer-planet orbiter missions for which a high data requirement exists. The advanced chemical-propulsion system offers the best performance for the Venus orbiter mission, and probably also for a more advanced Mars orbiter mission (although no cost data were available for this mission).

The analysis is based on a rather crude spacecraft model and on coarse estimates of the mass of its various subsystems. It should be noted, however, that for those subsystems common to all three spacecraft types, a change in performance or mass would have a similar effect in all three cases, and the relative spacecraft performances would not change much. On the other hand, a change in the specific mass of the payload powerplant, which of course is not a part of the nuclear-electric spacecraft, would have a considerable effect on the relative spacecraft performances. Barring a major improvement in payload powerplant specific mass, it is felt that relative performances presented are representative of what can actually be done.

The costs used in the analysis are recurring transportation costs; they include neither prorated development costs nor the cost of the payload. These latter costs cannot be estimated without making some assumptions about a future space exploration plan. All one can say is that for a very extensive plan for which the prorated development costs (for both the propulsion system and the payload) and the payload cost itself becomes small, the total cost approaches the recurring transportation cost.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 19, 1972,
790-91.

APPENDIX A

SYMBOLS

AU	astronomical unit, 1.496×10^{11} m
f	failure distribution
K_c	communication system constant, Mbit/sec $\times R^2_{AU}$/kW
K_p	ratio of active sensor power to communication power
K_{st}	structure fraction
M	mass, kg (lbm)
M'	total of power sensitive mass, kg (lbm)
m	mean time to failure, sec (yr)
n	learning constant
P	power, kW
P_u	power used by the payload, kW
Q	parameter in expression for relative mission value, $\dot{u}m/u_1$
R	distance, m (AU)
T	ratio of data gathering time to data transmission time
t	time, sec
u	amount of data, Mbit
$\dot{u}$	data rate, Mbit/sec
uv	weighted data, Mbit/sec
V	mission value, Mbit
v	data weighting value
α	specific mass, kg/kW (lbm/kW)
β	specific data rate, Mbit/kW
\$	transportation cost, \$
\$/V	cost per unit data return, \$/Mbit

Subscripts:

c	communication system

ca	communication system antenna
f	fixed mass
g	gross payload
o	optimum
p	payload powerplant
s	sensor system
sa	active sensors
saa	active sensors antenna
sp	passive sensors
st	structure
1	associated with the base data quantity

APPENDIX B

COMPARISON BETWEEN CONTINUOUS AND CYCLIC DATA RATES

In this appendix it is shown that a spacecraft designed so that both the sensors and communication gear operate at the same time (continuous operation) produces a higher data rate than a spacecraft designed so that first the sensors operate to collect data and then the communication gear operates to transmit it (cyclic operation).

Assumptions

The following assumptions apply to both continuous and cyclic operation.

(1) Mass of each major subsystem - the payload powerplant, the sensors, and the communication gear - is proportional to its input operating power.

$$M_p = \alpha_p P_p \qquad M_s = \alpha_s P_s \qquad M_c = \alpha_c P_c$$

(2) The data rate for both the sensors and the communication gear is proportional to input power

$$\dot{u}_s = \beta_s P_s \qquad \dot{u}_c = \beta_c P_c$$

(3) The total power sensitive mass allocated for the major subsystems is specified.

$$M_p + M_s + M_c = M'$$

Continuous Operation

In this case, the payload powerplant must provide sufficient power to operate both the sensors and communication gear at the same time.

$$P_p = P_s + P_c$$

Also, the rate at which data are obtained from the sensors must equal the rate at which they are transmitted to Earth.

$$\dot{u}_s = \dot{u}_c$$

$$\beta_s P_s = \beta_c P_c$$

$$P_s = \frac{\beta_c}{\beta_s} P_c$$

Applying these two constraints to the mass equation results in the following expression for data rate:

$$\dot{u}_c = \frac{M'}{\dfrac{\alpha_p + \alpha_s}{\beta_s} + \dfrac{\alpha_p + \alpha_c}{\beta_c}}$$

Cyclic Operation

The payload powerplant must be large enough in this case to provide power to that system which has the higher requirement.

$$P_p = \max(P_s, P_c)$$

Suppose that the power required by the sensors exceeds that for the communication gear. (The other case will be considered later.) The power from the payload powerplant must satisfy the active sensor power requirement.

$$P_p = P_s$$

This case also requires that the following inequality hold

$$\frac{P_s}{P_c} > 1 \rightarrow \frac{\dot{u}_c}{\dot{u}_s} < \frac{\beta_c}{\beta_s}$$

Over the time interval of a complete cycle, all the collected data must be transmitted.

$$\dot{u}_s t_s = \dot{u}_c t_c$$

Let the ratio of the collection time to the transmission time or the time ratio be designated by the symbol T

$$T = \frac{t_s}{t_c} = \frac{\dot{u}_c}{\dot{u}_s}$$

Applying the two constraints for this case to the mass equation results in the following expression for the transmission data rate when the communication system is operating

$$\dot{u}_c = \frac{M'}{\frac{\alpha_p + \alpha_s}{\beta_s} \frac{1}{T} + \frac{\alpha_c}{\beta_c}}$$

The average data transmission rate over a complete cycle (which is also the average data collection rate) is

$$\dot{u}_{c,\,av} = \dot{u}_c \frac{t_c}{t_s + t_c} = \dot{u}_c \frac{1}{T + 1}$$

$$= \frac{M'}{\left(\frac{\alpha_p + \alpha_s}{\beta_s} \frac{1}{T} + \frac{\alpha_c}{\beta_c}\right)(T + 1)}$$

The average rate can be maximized by selecting T such that the denominator of the expression is minimized. This value can be obtained by setting the derivative of the denominator with respect to T equal to zero. This produces

$$-\frac{\alpha_p + \alpha_s}{\beta_s} \frac{1}{T_o^2} + \frac{\alpha_c}{\beta_c} = 0$$

$$T_o = \sqrt{\frac{\alpha_p + \alpha_s}{\alpha_c} \frac{\beta_c}{\beta_s}}$$

With this value of T, the maximum average data rate can be written as

$$\max(u_{c,\,av}) = \frac{M'}{\left(\frac{\alpha_p + \alpha_s}{\beta_s}\frac{1}{T_o} + \frac{\alpha_c}{\beta_c}\right)(T_o + 1)}$$

$$= \frac{M'}{\frac{\alpha_c}{\beta_c} + \frac{\alpha_p + \alpha_s}{\beta_s} + 2\sqrt{\frac{\alpha_c(\alpha_p + \alpha_s)}{\beta_c\beta_s}}}$$

Comparison of Data Rates

By comparing the data rates for the two cases presented, it can be seen that the best data rate for cyclic operation would exceed that for continuous operation if the following inequality holds

$$2\sqrt{\frac{\alpha_c(\alpha_p + \alpha_s)}{\beta_c\beta_s}} < \frac{\alpha_p}{\beta_c}$$

Let us prove that cyclic operation results in a lower data rate by assuming this inequality to be valid and showing that this leads to a contradiction. The inequality can be rearranged into the following more convenient form:

$$\frac{\beta_c}{\beta_s} < \frac{1}{4}\,\frac{\alpha_p^2}{\alpha_c(\alpha_p + \alpha_s)}$$

The optimum value of T which is also the optimum value of the ratio of communication to sensor data rates is

$$T_o = \frac{\dot{u}_c}{\dot{u}_s} = \sqrt{\frac{\alpha_p + \alpha_s}{\alpha_c}\,\frac{\beta_c}{\beta_s}}$$

The following inequality results from the assumption that the sensor power exceeds the communication power.

$$\frac{\dot{u}_c}{\dot{u}_s} < \frac{\beta_c}{\beta_s}$$

Combining the two preceding expressions yields

$$\frac{\beta_c}{\beta_s} > \frac{\dot{u}_c}{\dot{u}_s} = \sqrt{\frac{\alpha_p + \alpha_s}{\alpha_c} \frac{\beta_c}{\beta_s}}$$

$$\frac{\beta_c}{\beta_s} > \frac{\alpha_p + \alpha_s}{\alpha_c}$$

Finally, combining this last expression with the assumed inequality results in

$$\frac{1}{4} \frac{\alpha_p^2}{\alpha_c(\alpha_p + \alpha_s)} > \frac{\beta_c}{\beta_s} > \frac{\alpha_p + \alpha_s}{\alpha_c}$$

$$\frac{1}{2} \alpha_p > \alpha_p + \alpha_s$$

This is a contradiction since the values of specific mass are all positive numbers. Therefore, the cyclic data rate is lower than the continuous data rate for the case in which the sensor power requirement exceeds that of the communication gear.

The opposite case in which the communication power exceeds the sensor power has yet to be treated. To do this, let us replace the sensor subscript with the communication subscript and vice versa on the terms in the equations presented. The resulting equations then represent the case in which the communication power exceeds the sensor power. It can be seen that the conclusion for this case is the same; that is, the cyclic data rate is lower than the continuous data rate.

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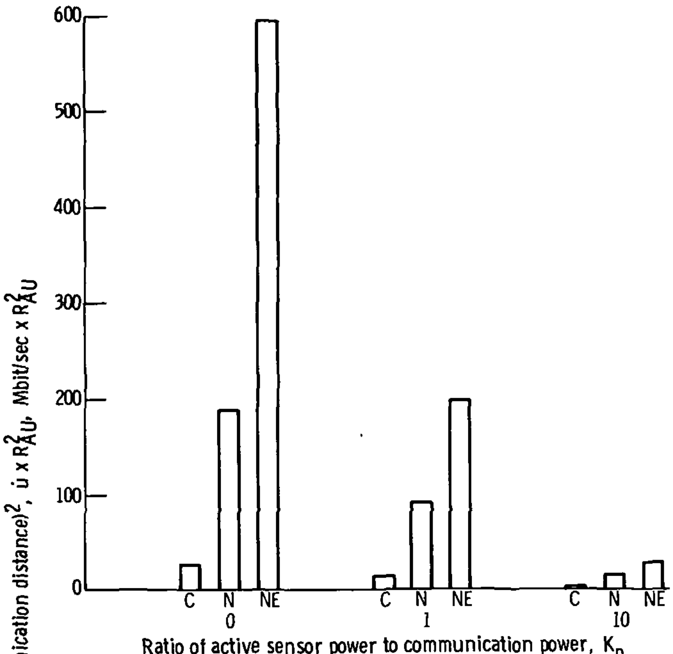
TABLE I. - TRANSPORTATION COSTS FOR HYPOTHETICAL

ADVANCED PROPULSION SYSTEMS

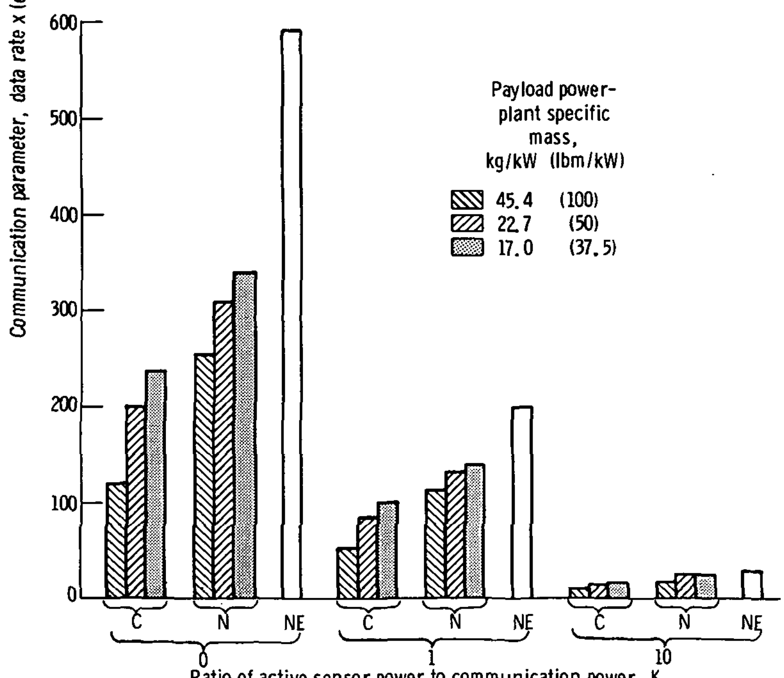
[Gross payload, 2000 kg; launch via Space Shuttle; orbital assembly permitted.]

Mission	Transportation cost $\$\times10^6$		
	Advanced chemical[a]	Improved NERVA solid core nuclear[b, c]	Nuclear-electric (120 kW)
0.1 AU solar probe	[d]17, 28	[d]44, 60	38
Mercury elliptic orbiter	36	57	38
Venus close orbiter	12	44	38
45° extra-ecliptic	[e]17	[e]44	38
EROS rendezvous	10	44	38
ENCKE rendezvous	27	50	38
CERES rendezvous	45	71	38
Jupiter elliptic orbiter	19	51	38
Saturn elliptic orbiter	19	46	38
Uranus elliptic orbiter	21	61	38
Neptune flyby	[d]17, 19	[d]51, 52	38

[a]Specific impulse, 470 sec; mass fraction, 0.9.
[b]Power, 25 kW.
[c]Costs shown do not include the 25-kW auxiliary powerplant.
[d]For Jupiter-swingby and direct trajectories, respectively.
[e]For Jupiter-swingby trajectories only.



(a) Outer planet missions. Radioisotope heat source payload powerplant, 227 kilograms per kilowatt (500 lbm/kW).



(b) Inner planet missions. Solar-electric payload powerplant, 22.7 kilograms per kilowatt (50 lbm/kW) at 1 AU.

Figure 1. - Comparison of data rates from 2000-kilogram gross payload delivered by chemical (C), nuclear (N), and nuclear-electric (NE) propulsion systems.

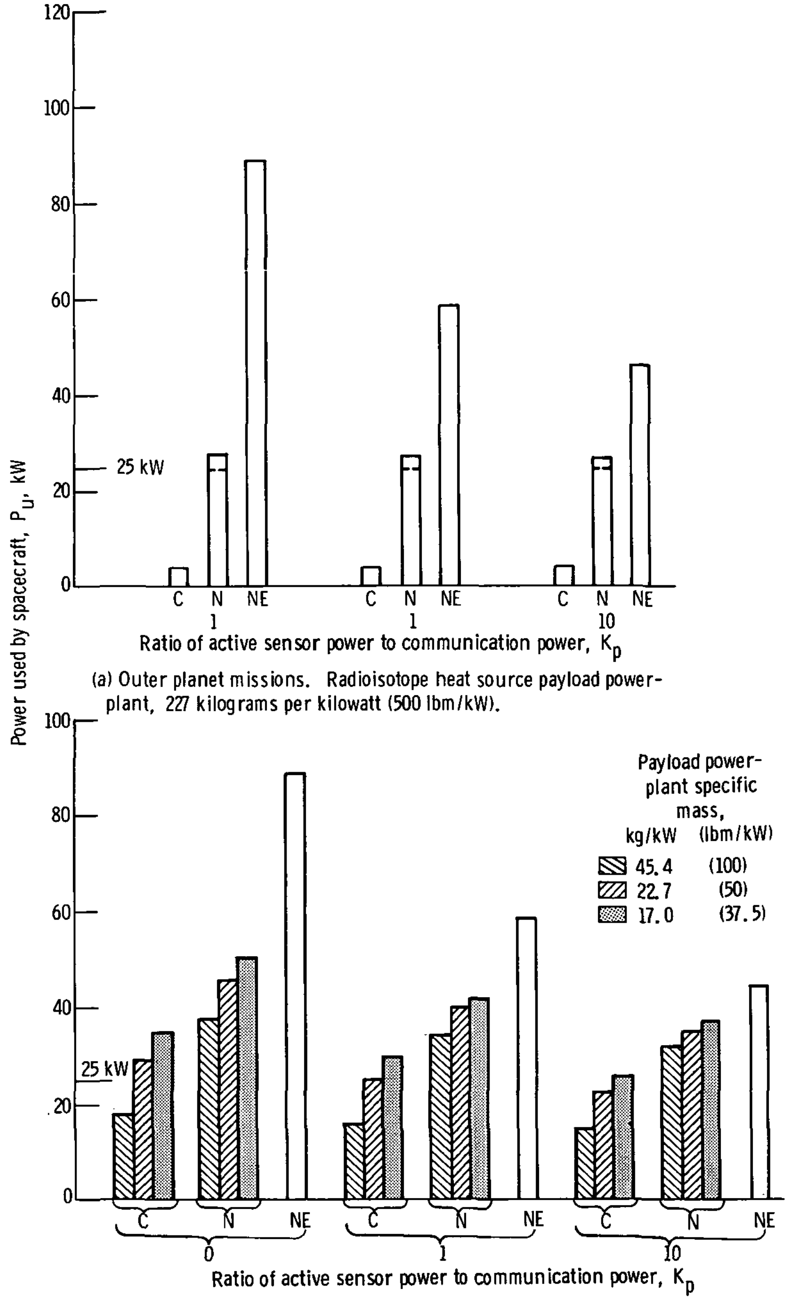


Figure 2. - Electric power used by 2000-kilogram gross payload delivered by chemical (C), nuclear (N), and nuclear-electric (NE) propulsion systems. (Note: 120 kW is available with NE system.)

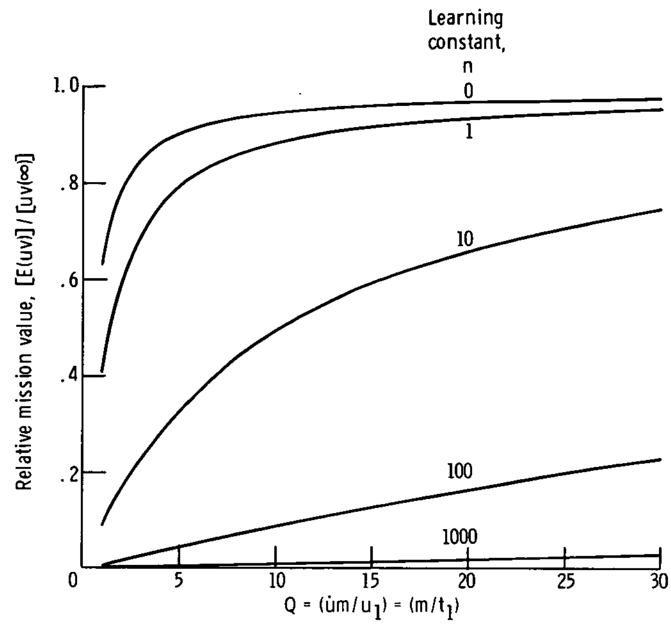


Figure 3. - Effect of data rate, mean time to failure, base data quantity, and learning constant on relative mission value.

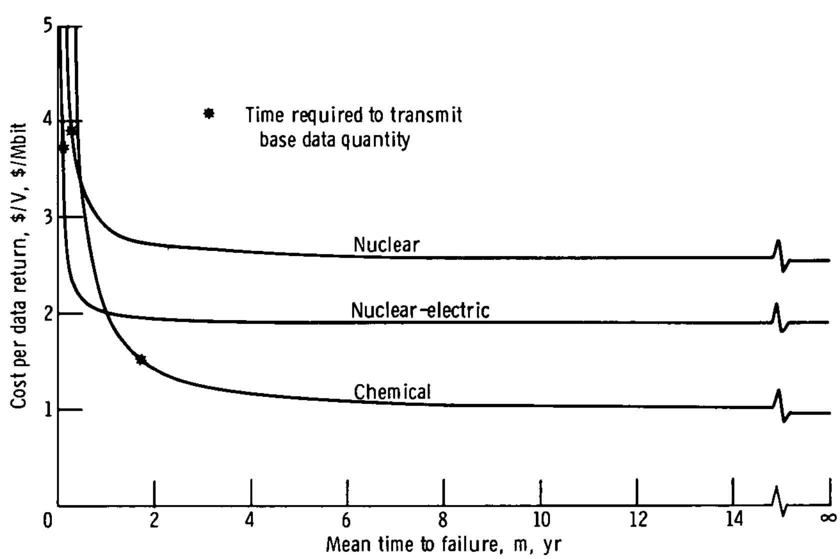


Figure 4. - Effect of mean time to failure on cost per unit data return for Jupiter orbiter mission. Base data quantity, 2×10^7 megabits; learning constant, 0; gross payload, 2000 kilograms (4410 lbm).

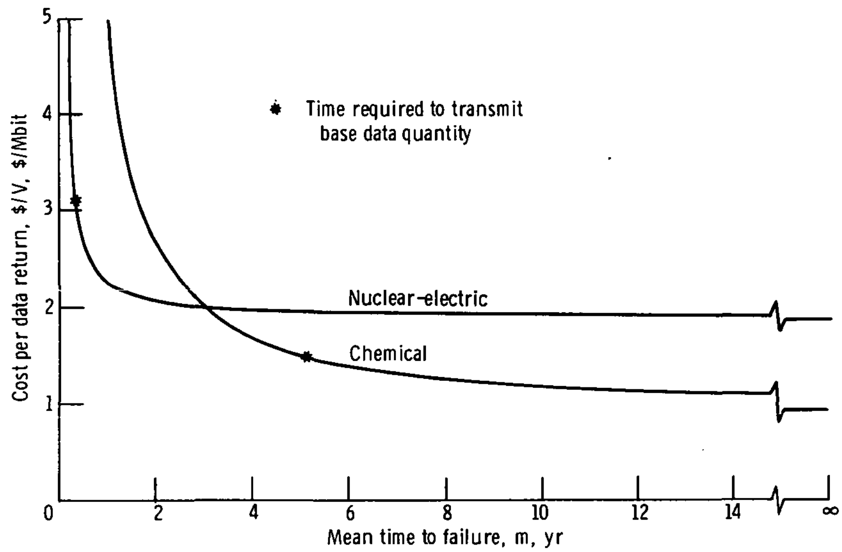


Figure 5. - Effect of mean time to failure on cost per unit data return for Saturn orbiter mission. Base data quantity, 2×10^7 megabits; learning constant, 0; gross payload, 2000 kilograms (4410 lbm).

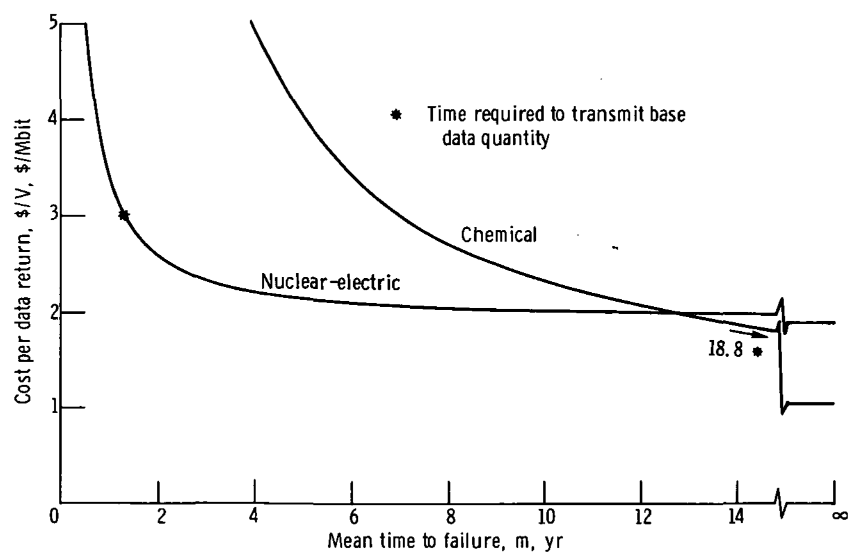


Figure 6. - Effect of mean time to failure on cost per unit data return for Uranus orbiter mission. Base data quantity, 2×10^7 megabits; learning constant, 0; gross payload, 2000 kilograms (4410 lbm).

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